The Future of Far-IR / Submillimeter Astrophysics with Single Dish Telescopes

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1 Introduction

Although far-IR – mm-wave astronomy has now been developing for several decades, access to this portion of the spectrum remains difficult and limited. Relative to their optical-wavelength counterparts, the submillimeter observatories are both small in units of wavelength and hot in units of photon energy, which imposes limits on their angular resolution and sensitivity. Nevertheless, even the modest far-IR and submillimeter observations obtained in the last two decades have revolutionized our understanding the physics and chemistry of the ISM, the formation of stars, and the cosmic history of these processes. The demonstration by COBE that about half of the radiant energy released in the universe since decoupling comes to us in the submm/far–IR has further underscored the scientific necessity of observations in this wavelength regime [8, 4, 5]. The next decade promises even greater discoveries, as new observatories and detectors are still pushing toward fundamental limits. The paper briefly outlines some of the exciting capabilities and scientific roles of new single-dish far–IR – mm-wave telescopes and their instruments.

2 Detector technologies

Over the past decade, one of the most important developments for far–IR through mm–wave astrophysics has been the push toward large–format direct–detector arrays. There are two key reasons why large arrays are important: (1) they provide a wider instantaneous field–of–view, thereby increasing the mapping speed; (2) they also allow better rejection of the "sky noise" due to atmospheric emissivity fluctuations, which is correlated across the array, and thereby provide better per–pixel sensitivities. Put together, these two factors provide a dramatic improvement in imaging capability.

For observations at $\lambda > 200\,\mu$m, bolometers are presently the most useful devices. Over the last 20 years, the mapping speed of bolometer arrays – equal to the ratio of the number of pixels to the square of a single pixel's sensitivity – has been improving at about a factor of two per year (faster than Moore's law !). Gains have been achieved in both single pixel sensitivity and array size. The individual detector elements are now achieving background-limited

performance for ground–based astronomy or CMB studies, and the number of pixels in a typical array is ≤ 400, which is about the practical limit of what can be achieved for individually–wired detectors in a sub-Kelvin focal plane.

Multiplexing technologies for the next generation of bolometer arrays are now under development by several groups for both CMB studies and submillimeter astronomy. The most ambitious example at present is the SCUBA-2 effort, slated to deploy 5000 close-packed superconducting transition-edge detectors in each of two (450 μm and 850 μm) arrays, to be read out with a SQUID-based multiplexer [6, 3]. However, while these technologies are very promising, they are in the early phases, and there remains the substantial task of fielding robust, sensitive astronomical instruments at the telescope.

The transition from the mm/submm to the far-IR ($\lambda < 200\mu$m) is a shift from ground-based observations to airborne and orbital platforms. The detectors of choice thus far have been the Ge:Ga photoconductors, which have flight heritage, require only modest cryogenic infrastructure (T$\sim$1.5 K), and can be naturally employed in large-format arrays using cryogenic CMOS multiplexers. These detectors arrays are the heart of the MIPS instrument on SIRTF (32×32 at 70μm, 2×20 at 160μm) and the PACS instrument on Herschel (16×25 at 90μm & 160μm), and will offer the most sensitive observations in the far-IR to date. Nevertheless, substantial room for improvement exists even at these shorter wavelengths: array construction is still very labor–intensive, which limits the array size, especially for stressed detectors at $\lambda > 100\,\mu$m; the quantum efficiencies are still relatively low; and the temporal response of these detectors requires sophisticated calibration protocols.

Coherent detection technology has also achieved impressive gains, driven by the needs of projects such as HIFI/Herschel and ALMA. Sensitive superconducting tunnel junction (SIS) mixers now operate up to 1.25 THz (240 μm), while superconducting hot–electron bolometer (HEB) mixers push to higher frequencies still, beyond 2.5 THz (120 μm). The improvements in local oscillator technology have been even more dramatic, especially the solid–state amplifier/multiplier chains developed for HIFI/Herschel, which are now capable of continuous tuning over > 100 GHz bandwidths and provide ample power for pumping SIS mixers at 1.25 THz and HEB mixers at 1.6 THz. These developments will revolutionize high–resolution terahertz spectroscopy, especially using airborne (SOFIA) and space (Herschel) platforms.

3 New single-dish facilities

A major initiative for the submillimeter / millimeter astrophysics community in the next decade is the Atacama Large Millimeter Array (ALMA). ALMA will be an inteferometric array of 64 12-meter antennas operating in the 230, 345, 460, 650, and 850 GHz atmospheric windows, and will be a very powerful instrument in these frequency bands with its unique combination of high

Table 1. Future ground-based single-dish observatories

Observatory	Dia.	Surf RMS	PWV (top 25%)	Refs
SCUBA2-JCMT	15 m	20μm	0.7 mm	[6]
APEX / ASTE	12 m	18μm	0.5 mm	[9, 10]
SPT	10 m	15μm	0.4 mm	[11]
LMT	50 m	70μm	0.8 mm	[12]
A-25	25 m	12μm	0.4 mm	(adopted)

sensitivity and very high spatial and spectral resolution. While future observatories must carefully consider their role in this context, the development of large–format cameras – one of the major technological trends over the past decade – offers powerful new capabilities for single–dish observatories. While not widely appreciated, it is in fact possible for future single-dish facilities equipped with wide–field direct–detector cameras to be competitive with ALMA in terms of absolute point–source continuum sensitivity, and orders of magnitude faster than ALMA for wide–field imaging, thereby securing a scientifically important role which is complementary to ALMA.

Consider the achievable (background-limited) sensitivity of a observatory:

$$\mathrm{NEFD_{BG}} = \frac{\mathrm{h}\nu\,[\bar{\mathrm{n}}(\bar{\mathrm{n}}+1)]^{1/2}}{\eta_{\mathrm{inst}}\,\eta_{\mathrm{tel}}\,\eta_{\mathrm{atm}}\mathrm{A_{tel}}(\mathrm{N_{pol}}\Delta\nu)^{1/2}}, \tag{1}$$

where $\bar{\mathrm{n}} = \epsilon_{\mathrm{load}}\,\eta_{\mathrm{inst}}\,(\mathrm{e}^{\mathrm{h}\nu/\mathrm{kT}} - 1)^{-1}$ is the photon mode occupation number (equivalent to the number of photons per second per Hz of detection bandwidth in a single spatial mode arriving at a detector). Although ALMA will offer a tremendous collecting area, single–dish telescopes can offer improvements in all the other factors appearing in Eq. (1). A reduction of the atmospheric opacity improves the sensitivity twice – in increasing the transmission (η_{atm}) and in reducing the background load (ϵ_{load}). The telescope efficiency η_{tel} is determined by the antenna surface accuracy according to the Ruze formula: $\eta_{\mathrm{tel}} \approx \eta_0 \exp[-(4\pi\epsilon_{\mathrm{rms}}/\lambda)^2]$. The ALMA antennas will have $\epsilon_{\mathrm{rms}} \sim 25\ \mu$m, leaving room for improvement at the high frequencies.

3.1 Direct-detection continuum observations

In addition to the sensitivity improvements that are possible by improving the telescope accuracy and atmospheric conditions, direct-detectors can provide additional sensitivity gains since one can couple both polarizations and the full bandwidth provided by the atmospheric windows. The advantage can be substantial – the 650 and 850 GHz windows are each 100 GHz wide, while ALMA will provide only 4–8 GHz instantaneous band. When combined with the efficiency factors, the per pixel sensitivity for a large single-dish telescope can be comparable to that of ALMA. The thin horizontal lines at the start

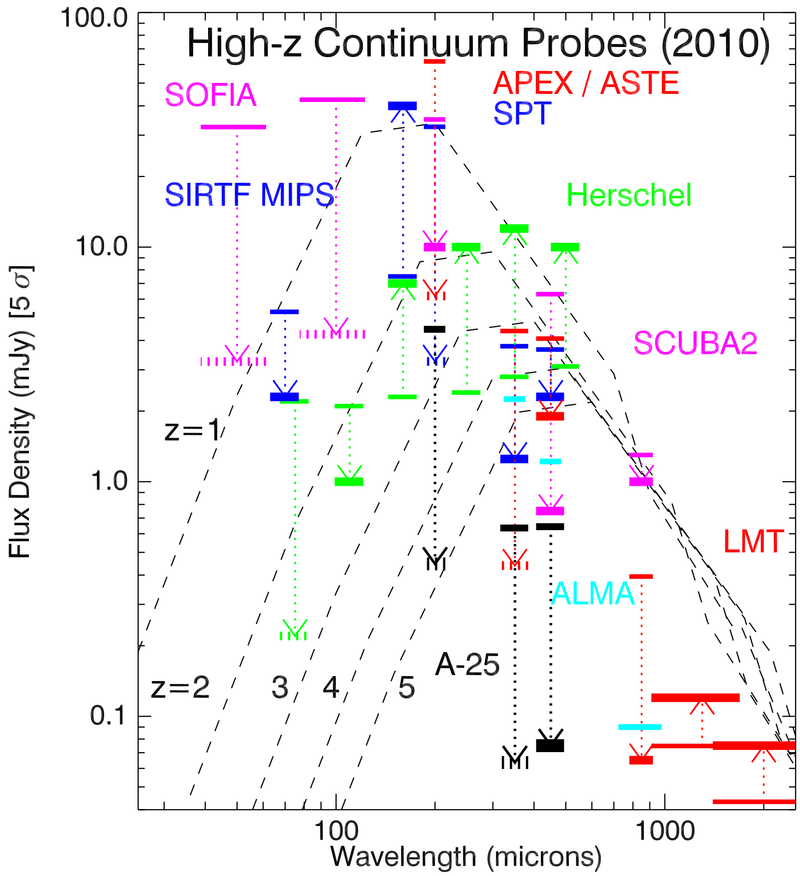

Fig. 1. Continuum capabilities in the far-IR . Raw sensitivities (5σ, 1 hour) are indicated with thin horizontal lines, taken from the references in Table 1, or calculated in the photon background limit assuming 50% instrument transmission. Estimates of the confusion limit due to extragalactic sources are indicated with thick horizontal lines at the termination of the vertical arrows. The confusion limits are taken to be 5 $\times$ the flux density at which there is 1 source per beam according to the source models of Blain et al. [1]. For instruments which are not confusion-limited in 100 hours, the 5σ, 100 hour sensitivity is plotted. Upward arrows imply measurements which are confusion-limited in less than 1 hour, downward arrows the converse. As a guide to the detectability of dusty galaxies, the Arp 220 SED at redshifts from 1 to 5 is overplotted in the light curves (taking $\Omega_{\rm matter} = .38$, $\Omega_\Lambda = 0.62$).

of the vertical arrows in Figure 1 plot the raw sensitivities of planned and potential observatories, listed with their parameters in Table 1. In the short submillimeter windows, the 10–15 meter class telescopes at excellent sites (APEX, ASTE, SPT) offer continuum sensitivities within a factor of 2–5 of

Table 2. Estimated far-IR / submm galaxy detection rates

	200μm	450μm	850μm	1.3mm
f_{nu}, most likely [mJy]	10–1000	10–50	2–7	1–5
Platform	*Galaxy Detection Rate* [hr^{-1}]			
SIRTF MIPS	70			
Herschel PACS	100			
SPT w/ 10^3 beams		150		
APEX / ASTE (300 beams)		25		
SCUBA2		20	100	
LMT			100	700
A-25 w/ 10^3 beams	7	900	2000	
ALMA		1	60	40

ALMA. The fiducial A25 telescope, a 25–meter with $\epsilon_{\rm rms} = 12\mu$m at a very dry site would be 2–5 times *more sensitive* than ALMA in these windows.

Large format direct-detector arrays allow rapid surveys

While the point source sensitivity of a large single-dish telescope can approach that of ALMA at the highest frequencies, the real advantage for single-dish telescopes is the tremendous mapping speed afforded by large-format focal plane arrays. As pointed out above, the mapping speed scales as the instantaneous solid angle and the inverse square of the sensitivity. To get a useful measure of survey speed, we convert the mapping speed to a galaxy detection rate, using power-law extrapolations to the observed source counts in a manner similar to [1]. As the estimates presented in Table 2 show, a single-dish telescope with a large detector array is much more efficient than ALMA for discovering the sources that make up the IR background. For example, at 450 μm, the most likely galaxy to be detected has a flux of a few $\times 10$ mJy. ALMA will be capable of detecting about one of these per hour, while SCUBA-2 will detect some 20 per hour, and a SCUBA-2 type array on the A-25 telescope could detect $\sim 10^3$ galaxies per hour. Of course, this rapid mapping speed provided large-format detector arrays applies to a wide range of science topics beyond the survey experiment outlined here.

Source confusion is a limitation for the 3-meter class telescopes

A key limitation of continuum surveys using single-dish telescopes is source confusion. When the number of sources in a beam approaches a substantial fraction of unity, extraction of fainter flux densities becomes difficult. Figure 1 includes estimates of this limit for the single-dish telescopes with the thick horizontal lines. We highlight some key points: 1) SIRTF and Herschel

will be quickly confusion-limited at their longest wavelengths, and the resulting effective sensitivities are insufficient to probe even bright ($L = 10^{12} L_\odot$) sources beyond $z \sim 1$. 2) Ground-based telescopes can in principle survey bright sources to $z \sim 5$ in the 350 and 450 μm windows, but with the existing and planned 10–15-meter telescopes this will require many tens of hours of observations (of a single field) in good weather, with careful attention paid to systematics. The fiducial A-25 telescope would be a factor of 5 more sensitive than the other telescopes at these wavelengths, and yet effectively not confusion-limited because of the smaller beam. 3) At 850 μm and 1.3 mm, the observed flux density is essentially independent of redshift, and beam confusion limits a 15-meter telescope to only the bright sources, as has been found with SCUBA. In principle, the 50-meter LMT could detect sources more than 10× less luminous than its 15-meter counterpart at 850 μm, but for $\lambda > 1$mm, the confusion again prohibits the detection of fainter sources.

3.2 Far-IR - mm spectroscopy with single-dish telescopes

ALMA will be an exquisite platform for spectroscopy and once commissioned will be the instrument of choice for spectroscopy at known frequencies and positions in its operational bands. Nevertheless, there will remain important scientific niches for spectroscopy that cannot be addressed with ALMA.

Full far-IR coverage provided by Herschel and SOIFA

Perhaps the most important is the full far-IR spectral coverage provided by Herschel and SOFIA, which will facilitate ISM studies not possible at other wavelengths. With few exceptions, the neutral atomic and ionized gas phases are probed with spectral lines at $\lambda < 200\mu$m, and the optical and near–IR transitions which might be important are typically obscured by dust. Key tracers of the molecular phase are also unique to the far-IR: examples include rotational transitions of the light molecular hydrides (e.g. OH, CH, HD), mid– and high–J CO lines which cool excited ($T > 100$K) molecular gas, and H_2O— a key constituent of the molecular ISM not observable from the ground. It is impossible to constrain the dense ISM conditions with ground-based observations alone, and much of our current understanding of these regions is based on far-IR spectroscopy from ariborne and space platforms: COBE, the KAO, ISO and SWAS. As the sensitivity of these observations improves by two or more orders of magnitude in the next decade with SIRTF, SOFIA and Herschel, we can anticipate significant advances in our understanding of the dense ISM phases advances.

Broad-bandwidth surveys with direct-detection spectrometers

Another niche in the context of ALMA's limited bandwidth is the capability to couple a large instantaneous band from point sources for spectral surveys.

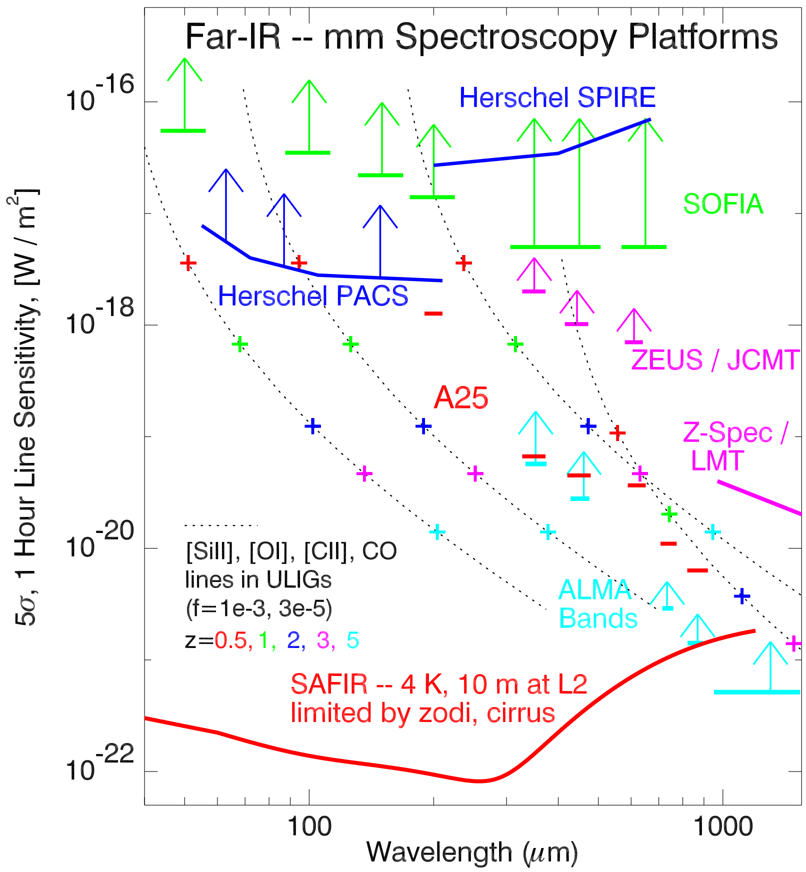

Fig. 2. Sensitivity provided by spectroscopy platforms in the far-IR and submillimeter. The upward arrows account for the effective sensitivity for line surveys, incorporating the time to cover the full atmospheric window for the ground-based instruments, or a 20% band for the SOFIA and Herschel instruments. Thin dashed curves show the intensities of diagnostic fine-structure and CO lines from high-redshift galaxies. Sensitivities for the Herschel and SOFIA instruments and ALMA are taken from the appropriate web pages, and Zeus and Z-Spec are referenced in the text. The sensitivities of SAFIR and the fiducial A25 telescope are calculated according to the photon noise limit assuming a 25% instrument transmission in a single polarization. SAFIR's background noise is due to zodiacal light and galactic cirrus, taken in regions of low intensity. *(Contact author for color version.)*

This is both a means of rapidly measuring several lines simultaneously, and potentially as a redshift measurement technique for optically-faint sources. The spectral survey rate increases as the instantaneous bandwidth of instrument, and even from the ground the instantaneous bandwidth can be

an order of magnitude larger than the 4–8 GHz coupled by ALMA. It can be shown that the most sensitive approach to broad-band spectroscopy of point sources is a low-order grating spectrometer [2], and for the first time such devices are under development for the submillimeter and millimeter. We highlight ZEUS, an echelle spectrometer for the 350 μm and 450 μm windows at the JCMT [7] and Z-Spec, a new waveguide grating spectrometer which covers the full 200–300 GHz window instantaneously [2]. In their windows, these ground-based spectrometers are more sensitive than those of Herschel and SOFIA because of the aperture size, and should detect diagnostic lines in bright sources ($L \sim \text{few} \times 10^{12}\, L_\odot$) up to z$\sim$3. Furthermore, such instruments combined with the A25 telescope could improve the sensitivity by an order of magnitude – probing the more more typical ($L \sim \text{few} \times 10^{11}\, L_\odot$) galaxies.

Potential of a cold space telescope

With Herschel, SOFIA, and the currently–envisioned ground-based spectrometers, we will have the capability to study the ISM conditions in local galaxies, and the very brightest galaxies out to redshifts of ~ 3, but not to the earliest epochs of galaxy formation. These platforms are limited by the background noise from the warm telescope itself (and atmosphere). However, dramatic improvements in sensitivity are still possible with a space telescope cooled to $T < 10\,K$. As an example, Fig. 2 includes the background-limited sensitivity for SAFIR, a 4 K, 10 meter observatory recommended in the McKee/Taylor Decadal Survey report. SAFIR will be an excellent far-IR spectroscopy platform – capable of detecting spectral lines in a Milky Way–type galaxy to redshifts of 5 or more. Note that a spectrometer can readily detect lines from several sources in the same beam, and thereby offers the potential to overcome the spatial confusion limit.

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